A toast to our health: our journey toward safe water

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Abstract Human beings have been struggling against epidemics for centuries but the first recorded epidemic in Egypt goes back to 3180 BC. Historically, it was not recognized that many of these “plagues” were waterborne. Advancements in medicine and microbiological sciences which identified and isolated the pathogens were needed before “safer” water could be achieved through advances in engineering. Disinfection of drinking water, introduced at the end of 19th century, considerably reduced the spread of cholera and typhoid fever. However, despite these innovations, waterborne disease epidemics continue even in the 20th century. We contend that this is partly because little attention has been paid to sewage practices and these are directly related to our health as the source of contamination, while much attention has been focused on drinking water. We propose that to achieve “safe water” and an improvement in global health worldwide in the 21st century, we must address wastewater problems learning from the past and we must use new advances such as molecular microbiology for pathogen discovery, and characterization and control of emerging and re-emerging waterborne diseases.

Keywords Epidemics; plagues; sewage pollution; waterborne disease; water microbiology

Water and health

Our life, well being and health are intricately tied to water. Civilization and our communities as we now know them developed and flourished over time as a result of the availability of freshwater supplies. In addition, large cities and populations were possible as a result of the ancient engineers who harnessed and managed water supplies building aqueducts, reservoirs, cisterns and plumbing/piping. In addition, to being able to transport and bring freshwater into cities, the ability to drain storm waters and control and dispose of wastes was developed. Along with the accumulation of people and concentration of our animals, development of infrastructure and use of the water for city life, agriculture and other purposes, came the inevitable pollution of the same water systems which provided the life-sustaining nourishment of the community and downstream communities. And with this pollution came disease. The first recorded account of a “pestilence” or “plague” as it was often referred to, was in approximately 3180 BC in Egypt’s First Dynasty. This early description of an epidemic demonstrated the devastation in terms of both morbidity (illness) and mortality (deaths) that occurs within a population as a result of massive widespread disease.

Waterborne disease is defined as the spread of infectious agents (microorganisms) through the direct contact with contaminated water causing illness in humans, transmitted through ingestion of drinking water and exposure to recreational waters. Known as fecal-oral, the bacteria, parasites and viruses that are excreted in the feces of infected individuals are spread through contaminated hands, surfaces, food, and most importantly for a community, water. Intestinal illness (diarrhea) was and is the symptom most often associated with these pathogens. Yet we now know that respiratory, skin, and eye infectious are associated with contaminated water, in addition these agents can cause
other health effects such as jaundice, liver and kidney impairment, paralysis, meningitis, and myocarditis. Many different symptoms were often described during the ancient times of pestilence and as with modern day waterborne outbreaks associated with sewage contamination, multiple pathogens and multiple symptoms are recorded.

We would contend that it was the contamination of water in particular with sewage and feces that led to many of the massive “plagues” of ancient times and that this remains today in the 21st century the single largest threat for exposing large numbers of people to serious illness and devastating communities and quality of life in some cases. Thus while there is much attention to drinking water systems, sewage systems are of equal importance but have been neglected throughout history. While individual water systems (wells and cisterns) the ability to carry water into the household allows a single household and family to obtain water, it takes a community effort to address storm waters, sewage and drainage (both in terms of effort and cost) (Crouch, 1993). Important lessons are to be learned from an historical perspective focused on water safety and the convergence of discoveries and advances in microbiology, medicine and engineering which can lead us toward addressing the challenges of today (Figure 1).

**Evolution of the medicine-microbe-environment connection**

It is clear from the chronology of historical events that advances in medicine and microbiology were necessary before environmental health could even begin to shed light on the role of water in the spread of disease (Beck, 2000). Ancient medicine addressed diagnosis of illness via the description of symptoms and the first recorded epidemic took place in ca. 3180 BC in Egypt. Early diseases were eluded to as “epidemic fevers” which was written in a papyrus ca. 1500 BC discovered in a tomb in Thebes, Egypt. Early in the history of medicine it was proposed that bad air, putrid waters, and crowding were all

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>3180 BC</td>
<td>First recorded epidemic in Egypt</td>
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<tr>
<td>2000 BC</td>
<td>Plague of Athens</td>
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<tr>
<td>580</td>
<td>Wealth responsible for a dysentery epidemic</td>
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<tr>
<td>1403</td>
<td>Quarantine established</td>
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<td>1546</td>
<td>“Seminaria” cause infection and epidemics</td>
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<td>1676</td>
<td>Microscopic observation of bacteria</td>
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<td>1773</td>
<td>Ozone identified</td>
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<td>1800</td>
<td>Chlorine kills germs</td>
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<td>1801</td>
<td>UV discovered</td>
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<td>1854</td>
<td>Fecal-oral transmission of typhoid fever</td>
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<td>1884</td>
<td>Germ theory by Robert Koch</td>
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<td>1893</td>
<td>Culture plate technique</td>
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<td>1903</td>
<td>Typhoid Mary, asymptomatic carrier</td>
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<td>1914</td>
<td>Largest bacterial water study</td>
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<td>1949</td>
<td>Electron microscope</td>
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<td>1952</td>
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<td>Cell culture for producing viral plaques</td>
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<td>1987</td>
<td>Gamma radiation of DNA</td>
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<td>1990</td>
<td>PCR</td>
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<td>1993</td>
<td>Largest waterborne cryptosporidiosis outbreak in Milwaukee</td>
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**Figure 1** History of key medical, scientific and engineering progress against waterborne diseases (Beck, 2000)
associated with disease and it was recognized that these maladies were contagious. “Plagues” were described and in particular associated with the decimation of the Greek Army near the end of the Trojan War (ca. 1190 BC) and with massive epidemics in Roman history in 790, 710 and 640 BC (Sherman, 2006) One of the best described plagues occurred in Athens in 430 BC. What appeared to be dysentery epidemics (enteric fevers) were described in AD 580. However, it was not until the 1500–1700s that advances first in microbiology lead the way for discoveries in medicine which solidified the idea of bacteria and led to the “germ theory”, pathogen discovery and the understanding of disease transmission.

The plague of Athens: an ancient waterborne disease outbreak?
The epidemic which devastated Athens as reported by the Greek historian Thucydides is often referred to as a medical mystery [Available online at: http://en.wikipedia.org/wiki/Plague_of_Athens; http://www.perseus.tufts.edu/GreekScience/Thuc.+2.47-55.html]. In 430 to 426 BC a massive epidemic was recorded, killing about 30,000 people. Illnesses were identified and described by the symptoms. The “plague of Athens” description included fever, inflammation, blisters on the skin, open sores, nervousness, and severe ulceration and watery diarrhea followed by death. It was noted that it was contagious and that there was some immunity as those that recovered were not attacked twice. Hypotheses have been developed on the etiology including influenza, smallpox, bubonic plague, typhus and \textit{Staphylococcus} (Langmuir et al., 1985). Some have suggested that this is an ancient disease that has since died out (Langmuir et al., 1985). Typhus was suggested yet it was not until 19th century that typhus and typhoid were distinguishable (Corfield, 1902). Many of the symptoms do follow those now known and ascribed to the disease typhoid. We would propose that one consider that multiple pathogens were the cause of this epidemic with typhoid being the principal disease associated with sewage contamination of the water supply. Recent molecular evidence from bodies exhumed from a mass grave (buried during the epidemic) has supported typhoid fever as a probable cause (Papagrigorakis et al., 2006). In addition, exposure to contaminated water could have also spread viral pathogens associated with respiratory disease and \textit{Staphylococcus}, which has been suggested as the cause of the gangrene (Langmuir et al., 1985).

Water and wastewater in Athens
Water in Athens was supplied by a series of public fountains, wells and cisterns (Crouch, 1993). Springs as well as engineered and piped water (rock cut tunnels and aqueducts) fed these systems which included rainwater (in the case of the Klepsydra, rainwater drained from the Acropolis). Drainage from storm water and sewage was flushed through drains in the alley or on the side streets between houses. Channels may have run outside the community to areas where the water was reused for crops, having recognized nutrient value as well (Crouch, 1993). Cess pools were also discovered and it is uncertain when these were no longer used in favor of drainage and flushing away from the home. There is also evidence that water pipes were laid and set near or within the drainage channels, or channels with freshwater were adjacent to those carrying wastewater. Combined sewer overflows where both storm water and sewer were mixed and captured were common. As the population increased to about 300,000, along with previous droughts a focus on enhanced water management including approaches used for water storage, collection of rain and runoff, transport, reuse and drainage in the karst terrain and limestone created a situation in which one could envision sewage cross-connections, and transmission of waterborne disease via drinking, bathing and through the irrigated food supply. Historical translations suggested that the disease was seen first in Ethiopia and “Suddenly falling
upon Athens, it first attacked the population in Piraeus, which was the occasion of their saying that the Peloponnesians had poisoned the reservoirs, there being as yet no wells there” (Langmuir et al., 1985).

Cholera and typhoid, the icons of waterborne disease

The hunt for the cause and cure of diseases began early with a marriage between medicine (including what is now known as epidemiology, study of disease transmission) and microbiology (Beck, 2000). The germ theory had been suggested in 1546 by Girolomo Fracastoro (publishing De contagione) and while infectious diseases were being described it was not until the microscope was invented in 1590 and refined in 1668 that bacteria were first seen in 1676 and then fully described in 1773 by Otto Frederik Muller (likely describing Vibrio). The “germ theory” was further solidified in 1840 and nine years later John Snow was able to show that cholera was transmitted through water (1849). Yet the translation of this knowledge to other organisms was slow. It was not until 1856 that it was suggested that typhoid fever was spread by feces and by then a scientific method to identify “contagious agents” using Robert Koch’s theories (1876) moved the study of cause-and-effect forward. A significant microbiological advancement was the invention of the culture technique using salts and yeast in 1872 and then a plating technique in 1881 using gelatin. Robert Koch not only addressed these plating techniques, but brought into microbiological practice the use of sterilization (what is now known as the autoclave). Gram stains came along and the Escherichia coli as we know and love it, was isolated (1884 and 1885, respectively) but it took 25 more years for the “coliform” to make its way into applications for assessing water and health risks, addressing fecal contamination. In that same time period (1884), Koch also isolated a pure culture of Vibrio and Georg Gaffky isolated the typhoid bacillus.

Typhoid has long been tied to our history and waterborne disease likely played a significant role well before it was appreciated. For US early colonists, in 1607, massive mortality occurred with up to 85% of the individuals dying in Jamestown, Virginia of what is believed to be typhoid brought over by a passenger on a ship from England (Sherman, 2006). Typhoid fever symptoms were described in 1659 but it was not until 1856 that William Budd suggested that typhoid was contracted through contaminated water; however this did not gain any acceptance until 1873 and was finally proven in 1884 as mentioned above.

In 1909, the USA and UK (on behalf of Canada, which became independent in 1931) signed the Boundary Waters Treaty aimed at preventing and resolving disputes between USA and Canada over waters forming the boundary between the two countries and which also established a formal binational body, the International Joint Commission (IJC). The treaty was originally intended to protect lake levels and navigability, however, this created the capacity for the IJC to get involved in pollution problems in boundary waters (Binder, 1972). There was a huge interest in water quality and the impacts on waterborne disease, primarily typhoid in the Great Lakes region. Major outbreaks had occurred in Chicago, Detroit and Milwaukee. This instigated one of the most comprehensive bacteriological studies ever conducted. There are several lessons to be learned from the 1914 IJC study. They promoted the use of the most technologically advanced methods (at the time bacteria samples were often grown in gel rather than agar (Durfee and Bagley, 1997)) and funded and set up laboratories for testing. Recommendations from the study which focused on coliform bacteria included the protection of the Lakes from wastewater discharges.

Studies on waterborne typhoid in the US and Canada between 1920 and 1930 reported 242 outbreaks, with 9,367 cases, an even more surprising 84,345 cases of dysentery (of
an unknown etiology) were associated with these outbreaks (Wolman and Gorman, 1931); in Canada, there were 40 outbreaks and 2,836 cases of typhoid. The high mortality finally precipitated drinking water treatment (both filtration and disinfection). But more importantly changed the way wastewater was handled. In 1833, about 150 people lived in the Chicago area, by 1880 more than half a million people lived and disposed of their waste into the water supply, Lake Michigan. Begun in 1900 it was not until 1922 that the Chicago Drainage canal was completed taking all wastewater down stream into the Chicago River and to the Mississippi (Capano, 2003). During this period, typhoid dramatically decreased and the disease was finally eliminated.

Cholera-like diseases were described early in China and Asia and certainly in Greece by 400 BC (Sherman, 2006). Massive outbreaks killing as many at 60,000 occurred in India in 1768, and these spread across Europe, reaching all the way to England. By 1832, the disease had reached NY, and erupted in 1873 particularly in port cities (New Orleans and NY). Thus John Snow’s advancement on the transmission via water played a significant role in moderating the disease spread and by 1854 the Vibrio cholerae bacterium was described. This organism spread quickly and is the first to be described in terms of a “pandemic”, which is the spread of disease throughout the globe. Cities such as New York City and other coastal communities were able to discharge wastes to the ocean, thus once disinfection began for drinking water, the cholera was readily eliminated in the developed world. It is curious that cholera was eliminated long before typhoid. This may be due to a number of reasons: (a) infectivity (Salmonella typhi has greater infectivity at low doses than V. cholerae); (b) survival in fresh water and wastewater (Salmonella survives better, as Vibrio prefers saline waters); and (c) carrier states for typhoid that contribute bacteria consistently to the sewage.

These diseases continue to ravage populations and communities. The current disease burden of typhoid is estimated at 17 million per year and 600,000 deaths [Available online at: http://www.who.int/ vaccine_research/diseases/typhoid/en/]; while cholera is reportable and the numbers range from 100,000 to 250,000 cases per year with about 2,000–3,000 deaths [Available online at: http://www.who.int/ wer/2005/wer8031.pdf]. We have to ask ourselves why the advances in our knowledge in medicine, microbiology and engineering have not controlled these diseases world-wide. It is our contention that lack of effort placed on community infrastructure and particularly sewage treatment that is of most immediate concern. Drinking water safety can be directed at the household level however storm waters, sewage and drainage as well as treatment must have community support (Crouch, 1993).

Other waterborne diseases of modern times

There is now a growing list of waterborne diseases of concern. Some are those which come from animals and humans, are zoonotic and can be transmitted across species barriers (Cryptosporidium and Giardia, Campylobacter, Salmonella). Thus animal waste in addition to human waste will need to be addressed. There are those associated with respiratory disease, cancer and neurological problems (Legionella, Helicobacter, polyomaviruses, and coxsackieviruses). Thus better disease surveillance and full understanding of the disease dynamics and transmission are warranted. And finally, there are possibilities of those which are rare and full of oddity that must be examined (SARS virus, influenza and anthrax). Our understanding of the diseases through advances in medicine/epidemiology and advances in microbiology will allow us to examine the transmission and waterborne disease potential thus focusing on the necessary engineering advances for community health and protection.
**Engineering advances and water safety**

In ancient time, there were almost no provisions for protecting against waterborne epidemics, as the etiological agents were not known, and neither the diseases nor their transmission were understood. Aesthetics played a primary role in the need to separate wastes from drinking water. Early on, controls were also attempted based on assumptions at the time on why sickness had occurred. During an epidemic of dysentery in France in 580, King Chilperic burned all the tax lists, believing that wealth was responsible for the epidemic (Beck, 2000). Other measures were more successful based on limiting exposures. In 1377, a 30-day isolation called “trentina” was officially imposed for ships entering the port of Ragusa (now Dubrovnik, Croatia) to protect its citizens from a plague epidemic (Gensini et al., 2004). This isolation was then fixed at 40 days for land travelers, from which derived our current word “quarantine”.

A major turning point in protection of community health and epidemics came in the mid-19th century. During a pandemic of the disease which had broken out in India in 1846, John Snow observed that cholera was transmitted through drinking water. He was then able to test his theory using one of the first engineering controls, by simply removing the handle from a water pump, which he suspected as the cause of the outbreak in a district in London (Vinten-Johansen et al., 2003). His achievement was enforced by the isolation of *Vibrio cholerae*, the bacteria that cause the disease in 1884 by Robert Koch (Beck, 2000). In the same period, a similar theory was suggested by William Budd on typhoid fever. The isolation of typhoid bacillus, now named as *Salmonella typhi*, by Georg Gaffky in 1884, supported his hypothesis (Beck, 2000). Both of these scientists proposed eliminating the exposure to the contaminated water supply and this initiated a search for an approach to disinfect or sanitize as was being done then in hospitals.

The discovery of water-borne transmission of these pathogens produced a drastic change for water and the ability to cope with these disease epidemics. Disinfection of drinking water to render or prevent spread of diseases was then started around the turn of that century. Chlorine was widely accepted as the measure because of its ease and cost-effectiveness in treatment. The first use of chlorine for sanitation of drinking water was by William Cruikshank in 1800 (Beck, 2000), almost 100 years prior to the medical discoveries mentioned above. While he suggested that chlorine could kill germs in water, the germ theory had yet to be substantiated and there was little wide-spread support of his ideas. However, the purification of “putrid waters” with chlorine gained some acceptance. It was not until 1896, that hypochlorite was first used temporarily as a disinfectant of drinking water during a typhoid epidemic in Austria-Hungary naval base of Pola (Baker, 1930). In the next year, “bleach solution” was used as a temporary measure to disinfect drinking water in Maidstone, England following a typhoid outbreak (Leal, 1909). These attempts proved that chlorine was effective as a disinfectant of drinking water and could be used to abate epidemics. Then this was followed by the first continuous chlorination of a water supply in Middelkerke, Belgium in 1902 (Whipple, 1906). Thereafter, chlorination of drinking water was accepted as a primary measure throughout the world and is still protecting our health from water-borne disease epidemics in the 21st century.

Other disinfection techniques were also introduced in the same period. Ultraviolet light, which was discovered by Johann Ritter in 1801, was first used for municipal drinking water in Marseille, France in 1901 (Beck, 2000). However, this technique was not widely used because of the high cost of UV lamps and the rapid spread of an easier technique, chlorination. Ozone was also introduced to water treatment in Oudshoorn, Netherlands in 1893, initially to deodorize water (Baker, 1930).
Some attempts were also made to disinfect sewage, particularly aimed at urbanized area. The first chlorination of sewage was conducted during the pandemic of cholera in the 1850s. The Royal Sewage Commission added chloride of lime to deodorize sewage in London, because odor was considered as the cause of water-borne diseases at that time (White, 1999). In 1893, chlorine was used as a disinfectant of sewage effluent in Hamburg, Germany (White, 1999). However, chlorination of sewage was not as widely implemented as it had been for drinking water, partly because the treatment of wastewater was not considered as important as the treatment of drinking water. Already available, septic tank and disposal to the subsurface was thought not to pose a risk and trickling sand filter technologies were being used in some areas to stabilize the wastes.

**Conclusion: the future of health-related water microbiology**

In the 21st Century, other diseases have changed the landscape of medicine. AIDS now infects millions of people worldwide and up to 30% of the populations in Africa. Waterborne diseases will be particular devastating to these individuals, and as already mentioned, there is a growing list of potential waterborne agents. Yet recent microbiological advances which include polymerase chain reaction (PCR) provide the tools necessary for monitoring any new agent of interest. Thus we must follow in the footsteps of Koch and Snow and continue to study and isolate the microorganisms of concern from water ways. The era of pathogen discovery is not over. We should be prepared to use all the microbiological advances to continue to understand the transmission of diseases through water. This must then be coupled with our knowledge in engineering to determine how to maintain and develop our infrastructure. The ancient Greeks knew that geology, hydrology and engineering were all important to a health, economics and well-being of a community. They knew that water was important to health. With the advances made in medicine, microbiology and engineering we can add to this body of knowledge to continue our journey toward “safe water” on a global scale.

We would recommend that currently the most significant areas to pursue are the following: (a) new advances should be applied to wastewater streams for pathogen discovery and for characterization of disease in our populations; (b) these data should be used to further an analysis of water quality and health status; (c) the assessment and recognition of community approaches and action should be focused on sewage, drainage and treatment; and (d) an analysis of household versus community based water and waste water systems and choices should be undertaken.

**References**


